Modelling of the Blast Furnace Based on the Multifluid Concept with Applications to Advanced Operations(多流体理論による高炉数学モデルの開発とその高度操業への応用)

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論文内容要旨

Chapter 1. Introduction

The iron-making blast furnace is a counter current moving bed chemical reactor whose main purpose is to reduce iron oxides to iron. The major phases in the furnace are gas, lump solids (ore and coke), liquid (molten iron and slag), and powders (tuyere injectants or dust from the lump solids). Previously, many mathematical models of the furnace have been proposed, but most have considered only two or three phases, and usually have made many simplifications to the governing equations. In this thesis, a mathematical model is presented which simultaneously solves rigorous conservation equations for all four phases, including multiphase heat, mass and momentum exchange. This model is validated with actual operational data, then used to analyse several advanced methods of furnace operation.

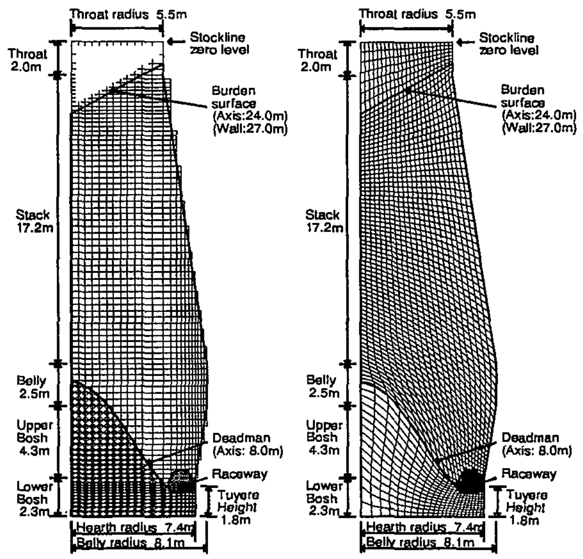


Fig. 1 Orthogonal grid (left) and BFC grid (right) for the same furnace.

One perceived weakness in the present model is the description of the powder motion. In order to better understand the transport of powder through a packed bed under the influence of gas drag and gravity, experimental work was conducted. The experimental results are used to develop models of powder dispersion and static holdup.

Chapter 2. Mathematical Formulation of a Multiphase Model of the Blast Furnace

The conservation equations for all four phases in the furnace are expressed by Eq. (1).

$$\frac{\partial}{\partial x}\left(\varepsilon_i \rho_i u_i \psi\right)+\frac{1}{r}\frac{\partial}{\partial r}\left(r\varepsilon_i \rho_i v_i \psi\right)=\frac{\partial}{\partial x}\left(\varepsilon_i \Gamma_\psi \frac{\partial \zeta}{\partial x}\right)+\frac{1}{r}\frac{\partial}{\partial r}\left(r\varepsilon_i \Gamma_\psi \frac{\partial \zeta}{\partial r}\right)+S_\psi \quad .....(1)$$

This equation is discretised over a non-orthogonal grid, which may be simplified to an orthogonal grid, and then solved using the control volume method. **Fig. 1** shows typical grids used by the model. Phase properties such as density, temperature, thermal conductivity, *etc.*, are calculated from the phase composition, enthalpy and pressure. Interphase drag, interphase heat transfer and rates of chemical reactions and phase transformations are calculated from correlations and rate equations reported in literature where available.

Chapter 3. Powder Dispersion in a Packed Bed

Two dimensional dispersion of powder being carried by gas through a packed bed was experimentally investigated. The gas flow pattern was plug flow. Powder was injected through a small section of the inlet face of the packed bed. The transient change in powder holdup was recorded photographically. The powder volume fraction was calculated from the photographic results using computer image analysis. **Fig. 2(a)** shows a typical result for the powder volume fraction distribution in the packed bed 5 minutes after commencing powder feed. Powder holdup was analysed as a function of gas speed, packed bed particle diameter, powder feed rate and inclination of the gas flow direction from the vertical. Two theoretical models were developed and tested against the experimental data. The first model was of powder dispersion by the packed bed. **Fig. 2(b)** shows the powder holdup calculated using this model for the same conditions as in Fig. 2(a). The second model was of static holdup at packed particles' contact points. Both models reproduced observed results.

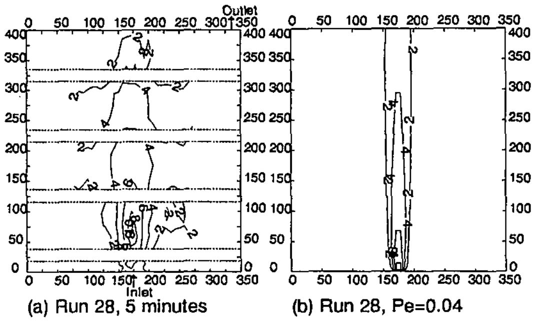
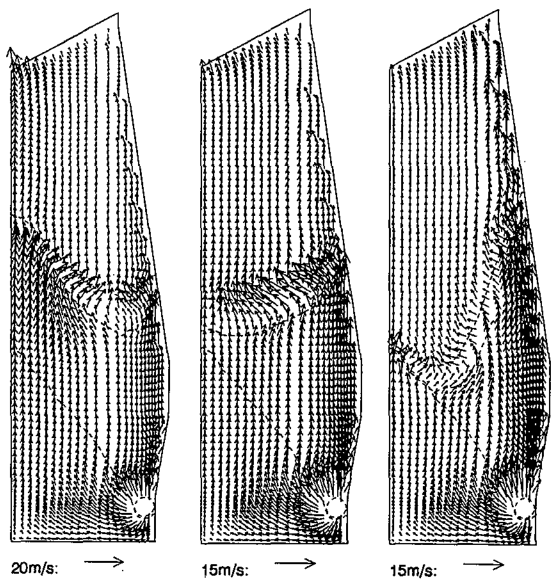


Fig. 2 Powder volume fraction (a) measured 5 minutes after starting powder feed, and (b) calculated using Pe_f=0.04.

Chapter 4. Four Phase Motion and Heat Transfer in the Blast Furnace

Four phase motion and heat transfer was analysed using simplified forms of the chemical reactions and phase compositions. Case studies were conducted analysing the effects of burden distribution and pulverised coal (PC) injection rates. The calculated cohesive zone (CZ) shape and liquid flux entering the hearth show strong correlation with the ore:coke distribution at the burden surface, but can be influenced by the deadman also, as shown in **Fig. 3**. Powder flow is strongly coupled to the gas velocity field. Large powder holdup is predicted



(a)Normal (b)Uniform (c)Reverse

Fig. 3 Influence of ore:coke distribution on cohesive zone shape and gas velocity.

immediately behind the raceway as the powder collides with the coke packed bed. The model also predicts that with increasing PC rates the powder dynamic holdup increases linearly in the bosh and quadratically in the stack.

Chapter 5. Four Phase Blast Furnace Reaction Analysis - Model Validation and Submodel Case Studies

The model developed in Chapter 2 is firstly validated using measured furnace data. The model is able to correctly predict the two dimensional temperature distribution within the furnace, and also to predict the measured production rate and other parameters for a large number of monthly average data sets from two different furnaces.

In a subsequent base case calculation the model predicts rapid initial reduction of hematite to magnetite, but slow reduction from magnetite to iron due to the endothermic nature of the reactions. Predicted gas and liquid phase compositions are plausible, but the powder dynamic holdup distribution is sensitive to the powder consumption processes in the raceway.

Two model extensions are also presented. First, silicon transfer is analysed. The inclusion of silicon transfer results in a cooler bosh due to silica reduction, giving a slightly lower liquid outflow temperature than that calculated in the base case, and a higher CZ due to the exothermic SiO re-oxidation, as shown in **Fig. 4**. Coke ash silica and molten slag silica both contribute to SiO generation, however in the present calculation hot metal silicon is more strongly dependent on slag silica due to longer SiO-metal contact times.

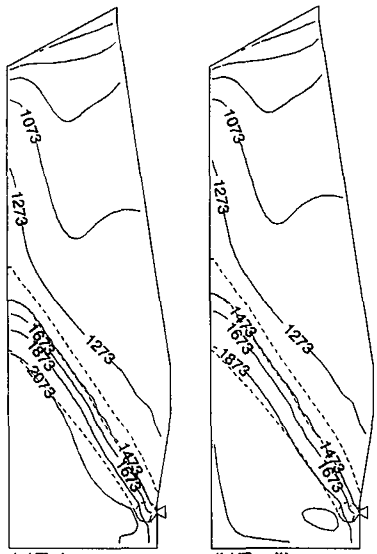


Fig. 4 Solid temperatures (K) for (a) the base case and (b) with silicon transfer.

A second extension is the inclusion of static liquid holdup. Three correlations for static holdup are investigated. In all cases there is an increase in liquid transport towards the raceway region due to static liquid carried by solids moving between the deadman and cohesive zone. The model is sensitive to the treatment of static holdup in the raceway region.

Chapter 6. Prediction of Blast Furnace Performance Under Novel Operating Methods

This chapter analysed blast furnace performance under two novel operating methods. The first method considered the recycling of furnace top gas for reinjection at the tuyeres. Three methods of top gas recycling were investigated. **Fig. 5** shows calculated changes in production and fuel rate for the three methods at fixed hot metal temperature. Simple replacement of normal blast gases with recycled top gas causes productivity to decrease and fuel rate to increase. Likewise, oxygen enriched blast replacement has similar effects, although the severity is less. Both of these methods reduce furnace efficiency. Hot reducing gas replacement, where recycled top gas is stripped of CO_2, leads to an increase in production of up to 25% with a decrease in fuel rate of 20%.

The second method considered is the charging of scrap with the burden. Three different scrap charging patterns were investigated at constant hot metal temperature and at constant top gas temperature. **Fig. 6** shows calculated changes in production and fuel rate for the three patterns at fixed top gas temperature. In all cases, productivity increased and fuel rate decreased as scrap:ore mass ratio increased. At constant hot metal temperature, top gas temperature decreased due to the scrap sensible heat demand. At fixed top gas temperature, the optimum scrap charging pattern was to charge scrap over the outer half furnace radius.

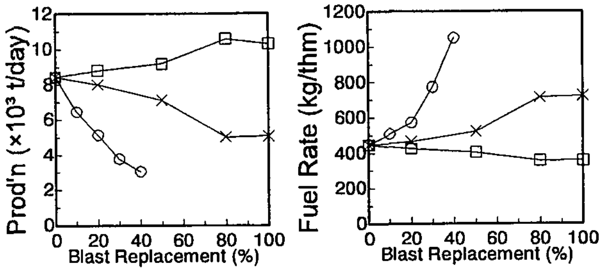


Fig. 5 Calculated change in production and fuel rate with top gas recycling at fixed hot metal temperature. O: simple recycling; ×: oxygen enriched recycling; □: hot reducing gas recycling.

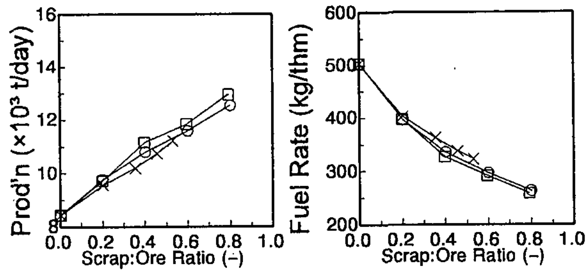


Fig. 6 Calculated change in production and fuel rate with scrap:ore mass ratio at fixed top gas temperature. O: uniform scrap charging; ×: centre scrap charging; □: wall scrap charging.

Chapter 7. Conclusions and Recommendations

A mathematical model of the blast furnace has been presented which solves coupled conservation equations for the four principle phases in the furnace. The model has been validated against operational results, and used to analyse several advanced operational methods. Also, powder dispersion in a packed bed has been investigated experimentally. The experimental results are expected to enhance the accuracy of the future blast furnace models.

審査結果の要旨

現在の製鉄法の主流を占める高炉－転炉法はエネルギー多消費型プロセスであり、その高効率化はエネルギー，環境問題への寄与が極めて大きい。本研究はこれまで詳細な測定が困難であるとされてきた高炉内の運動，伝熱，反応挙動を理論的に推算可能な数学モデルを多流体理論に基づいて開発し、これを新規操業の有用性の検証と高効率操業条件の探索に応用したものであり、全７章からなる。

第１章は緒論であり、本研究の背景および目的を述べている。

第２章では、高炉炉下部に存在する気体（反応ガス），固体（鉱石，コークス），液体（溶銑，スラグ）および粉体（微粉炭，微粉コークス）を、それぞれ流体として取り扱う多流体理論を提案するとともに、各流体の運動，伝熱，反応挙動とこれらに及ぼす異相間相互作用を定式化し、高炉プロセスの数学モデルを提案している。

第３章は、均一な直方体型充填層に対してその一端から気流を導入し、さらにその特定部分から粉体流を流通させた際の粉体の滞留量分布とその変化を測定することで、充填層中を流通する気固二相流における粉体の分散挙動の測定と定式化を行っている。

第４章では、第２章において開発した数学モデルのうち流動と伝熱に関する部分を高炉内の流動・伝熱解析に応用し、炉内の充填状態，操業条件の変更による各物質の供給量変化および各相の物性値・特性値が炉内状態に及ぼす影響について検討し、鉱石の溶解帯形状，圧力損失等の変化を明らかにした。

第５章は、開発したモデルを実際に稼働中の高炉の操業条件に応用し、その解析結果を実高炉における二次元温度分布の測定結果および各種操業パラメータと比較することで、モデルの妥当性を検証している。また炉内で生じる物質循環反応（Si 移行反応）が炉内の伝熱速度に及ぼす影響について定量的に明らかにした。

第６章は、高炉排ガスの再循環法およびスクラップ装入法という二つの新規操業法に対して開発した数学モデルによる操業解析を応用し、その有用性と操作可能範囲および最適操業条件の探索を行っている。その結果これらの操業法の導入による燃料消費量の低減および操業パラメータの変化が定量的に明らかにされるとともに、原燃料投入の分布が重要な因子でありその最適化への指針を与えている。

第７章は総括である。

以上要するに本論文は、高炉法による製鉄プロセスにおける移動現象を多流体理論に基づいて表現する数学モデルおよびその数値解析法を開発し、実高炉および新規操業条件下での定量的な内部現象の把握と性能評価を可能にしたものであり、金属工学の発展に寄与するところが少なくない。

よって本論文は博士（工学）の学位論文として合格と認める。